Analytical calculations of functional connectivity and of information processing capabilities of neural networks of arbitrary size

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The function of the brain is likely to depend crucially on its ability to dynamically exchange and integrate across neural populations [1]. The wiring of synaptic connections, also known as structural connectivity, is undoubtedly one of the main factors that shape the function of the brain. However, the interaction between the activities of different neural populations (typically measured as functional connectivity, namely the set of the statistical dependencies between and within its neural populations), depend also on yet largely unknown network mechanisms that modulate the strength of each connection [2]. Thus, the relationship between structural and functional connectivity is complex and yet to be understood, and it is the subject of intensive mathematical investigations [3,4]. Here we present a new first-order perturbative method to evaluate analytically the functional connectivity of a stochastic neural network in terms of its cross-correlation structure. We applied it to a network model composed of finite-size excitatory and inhibitory populations of neurons, described by a voltage-based differential equation with an input with a weak normally distributed stochastic component, used as perturbative parameter. The advantage of this technique is that it can deal with finite-size networks and correlated sources of noise. Moreover, when integrated with the Fokker-Planck equation of the network, this method allowed us the analytical determination of Shannon information between groups of neurons (which measures the functional connectivity between the network's populations), and of the Fisher information carried by the activity of groups of neurons of arbitrary size about features of the input current. The latter permitted us to compute under which conditions correlations improve or instead limit the encoding precision of the network, a problem under current intense debate [5,6]. To get a more complete understanding of the network, we also performed a numerical and analytical bifurcation analysis of the neural equations as a function of the input without the stochastic term, since in our weak-noise regime the system is mainly driven by the deterministic equations. In particular, we calculated the stability regions of the network, the emergence of oscillations through Hopf bifurcations and their frequency changes through homoclinic bifurcations, and finally the saddle-node manifold. We found the latter to be very important to explain analytically some counter-intuitive behaviors of the functional connectivity, such as an increase of variance and correlation of neural fluctuations close to network phase transitions that have been proposed by other to resemble the changes in consciousness due to anesthesia [7]. Finally, we studied the network's behavior in response to oscillatory stimuli by quantifying the vibrational properties of the system (i.e. amplitude attenuation, phase shift and resonance frequency) as a function of the intensity of the synaptic weights, completing the description of the role of the structural connectivity in shaping the activity of the network.

References

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